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Regional climate-model performance in Greenland firn derived from *in situ* observations

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Recent record-warm summers in Greenland (Khan *et al.* 2015) have started affecting the higher regions of the ice sheet (i.e. the accumulation area), where increased melt has altered the properties of firn (i.e. multi-year snow). At high altitudes, meltwater percolates in the porous snow and firn, where it refreezes. The result is mass conservation, as the refrozen meltwater is essentially stored (Harper *et al.* 2012). However, in some regions increased meltwater refreezing in shallow firn has created thick ice layers. These ice layers act as a lid, and can inhibit meltwater percolation to greater depths, causing it to run off instead (Machguth *et al.* 2016). Meltwater at the surface also results in more absorbed sunlight, and hence increased melt in the accumulation area (Charalampidis *et al.* 2015). These relatively poorly understood processes are important for ice-sheet mass-budget projections.

Regional climate models (RCMs) simulate energy fluxes and mass transfer between the atmosphere and the ice-sheet surface. Their accuracy depends on model physics and numerical sophistication, as well as on the atmospheric forcing implemented at their boundaries based on global weather reanalyses or general circulation models (see below). Ice-sheet mass-budget calculations using RCMs therefore need to be validated against observations. In this study, we evaluate the performance of the subsurface scheme of the HIRHAM5 RCM (Christensen *et al.* 2006) by comparing it with firn temperatures measured at the KAN_U weather station from April 2009 to September 2013 (Charalampidis *et al.* 2016). We determine the reasons for temperature biases by comparing HIRHAM5 with a validated surface energy balance (SEB) model over the same period (Charalampidis *et al.* 2015).

Firn temperature measurements

Situated 1840 m above sea level (a.s.l.), KAN_U is the uppermost automatic weather station at an elevation transect of meteorological and mass-budget monitoring sites in the south-western part of the Greenland ice sheet (Charalampidis *et al.* 2015; 67°0′N, 47°1′W). The long-term equilibrium line altitude, where summer ablation balances winter accumulation, is 1553 m a.s.l. (Van de Wal *et al.* 2012). KAN_U is located above that, and thus monitors melt, percolation and refreezing in firn. Established in April 2009, the KAN_U record includes the high melt seasons of 2010, 2011 and 2012 (Charalampidis *et al.* 2015).

The subsurface temperature analysis by Charalampidis *et al.* (2016) revealed that in the 2010 and 2011 high melt summers, meltwater occupied the pore volume between 2 and 3 m below the surface (Fig. 1A). The continued refreezing of this temporarily retained, near-surface liquid water until after the end of both the 2010 and 2011 melt seasons contributed to the merging of superimposed annual ice layers. These ice layers were observed at depths between 2.5 and 5.5 m in May 2012 (Machguth *et al.* 2016). Subsequently, meltwater by the end of August 2012 was confined in the upper 2.5 m relative to the May 2012 surface, with subsequent runoff in response to the intense surface lowering. By September 2012, after the onset of cold atmospheric conditions, refreezing occurred below 2.5 m by meltwater percolation to the limited available pore volume between the ice layers. The latent heat release by refreezing at depth in autumn 2012 resulted in a high December–January–February average firn temperature of –6.1°C between 2 and 5 m depth (Charalampidis *et al.* 2016), while the accumulating snow cover provided thermal insulation from the cold winter atmosphere.

The HIRHAM5 regional climate model

We use HIRHAM5 at 5 × 5 km horizontal resolution, which has demonstrated good results for the climate of the Greenland ice-sheet margin (e.g. Langen *et al.* 2015). It uses 31 vertical atmospheric levels and a time step of 90 seconds. At the lateral boundaries, the model is forced at 6-hour intervals with wind, temperature, specific humidity and atmospheric pressure from the ERA-Interim weather reanalysis (Dee *et al.* 2011). The model computes processes in the atmosphere, including clouds, solar radiation attenuation, longwave radiation emission and precipitation. These variables then determine the energy balance and mass budget at the surface. Daily-smoothed, MODIS-derived surface albedo regulates solar radiation absorption (Box *et al.* 2012).

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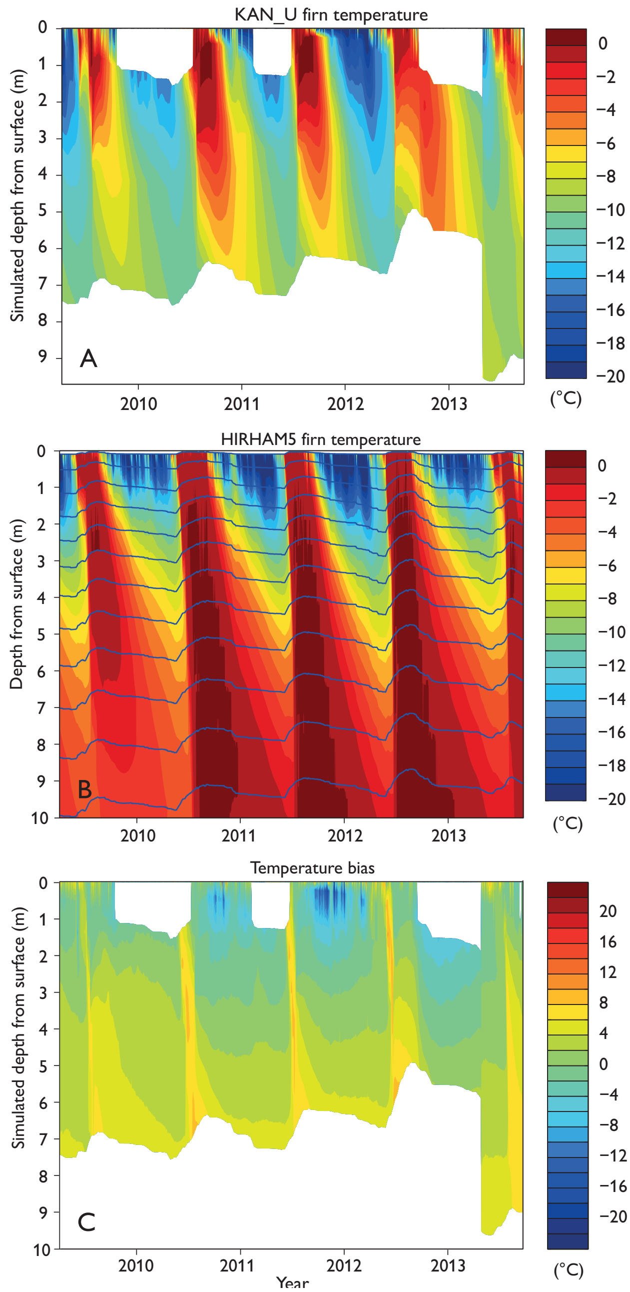

Fig. 1. **A**: Firn temperatures observed at KAN_U (Charalampidis *et al.* 2016). **B**: HIRHAM5-simulated firn temperatures at the location of KAN_U, with the blue lines indicating the simulated depth of the mid-point of each layer. **C**: The difference between the two (B minus A).

The subsurface scheme (version 7.11) uses 25 layers with a total depth of 70 m water equivalent (*c.* 78 m physical distance at KAN_U). It accounts for heat diffusion, vertical water transport and refreezing, as well as temperature, and pressure-dependent densification of snow and firn after Vionnet *et al.* (2012). Each layer can hold liquid water corresponding to 2% of the snow pore volume and excess water percolates downward to the next layer. Water is assumed to run off when it encounters a layer of pore close-off density (i.e. 830 kg/m^3; Herron & Langway 1980). Before runoff occurs, the water is available for superimposed ice formation onto the ice layer.

Simulated versus observed firn temperatures

The HIRHAM5-simulated firn temperature evolution at KAN_U is shown in Fig. 1B. A seasonality following surface forcing is evident: 0°C from summer melting and about –20°C near the surface in winter. During the melt season, the simulation shows maximum firn temperature at depths *c.* 2 m in 2009 and *c.* 9 m in 2010, and even deeper in the following years. Accordingly, the extent of the simulated temperate layer (i.e. temperatures between –1 and 0°C) increases from 6 m in summer 2009 to more than 10 m in 2010 and the following melt seasons. The propagation of the temperate conditions at depth suggests concurrent meltwater percolation, refreezing and latent heat release. However, the observed temperate layer did not extend below 3 m at any point (Fig. 1A).

The firn temperature bias (simulated minus observed) is shown in Fig. 1C by comparing the interpolated HIRHAM5 values at observational depths with the observed ones. The model bias is mostly positive and increases with depth. Typical differences for the deepest measurements range between +6 and +12°C. Negative differences occur during winter at depths less than 2 m in all years except 2012. In winter 2012, the RCM underestimates firn temperatures as deep as 3 m.

Table 1 shows the average summer and winter HIRHAM5 firn temperatures at specific depths, and the biases. The summer difference averaged over all available depths is +5.7°C. Better agreement between HIRHAM5 and observations is found for winter with an average difference of +3.2°C. In winter 2012, HIRHAM5 agreement is best, and is the only instance in the comparison when model bias at any of the listed depths was negative. This agreement is indicative of the abnormally warm conditions that persisted in the top 2–5 m firn after the extreme 2012 melt season, but also of the efficiency of the HIRHAM5 simulation of surface-heat transfer into firn.

Explaining the bias

Subsurface differences between RCM and the observations can be due to differences in surface melt, quantity and depth of meltwater percolation and the timing of refreezing.

Table 1. Average HIRHAM5 firn temperatures, linearly interpolated to specific depths (left columns) and biases (right columns) at KAN_U (Charalampidis *et al.* 2016)

Depth	2009		2010		2011		2012		2013	
Summer temperatures (°C; June–July–August)										
2 m	–2.9	+3.1	–0.4	+4.3	–1.9	+3.5	–0.3	+5.3	–4.2	+3.5
3 m	–3.6	+4.7	–1.0	+5.5	–2.3	+4.7	–1.1	+5.9	–4.4	+4.5
4 m	–3.6	+6.1	–1.5	+6.5	–2.3	+6.0	–1.4	+6.9	–4.1	+5.1
5 m	–3.6	+6.3	–1.7	+7.1	–2.1	+6.8	–1.3	–	–3.6	+5.7
6 m	–3.4	+6.7	–1.8	+7.9	–1.7	+7.7	–1.2	–	–3.0	+6.4
Following winter temperatures (°C; December–January–February)										
2 m	–9.5	+3.2	–8.9	+0.7	–12.2	+0.3	–8.7	–2.0	–	–
3 m	–6.5	+4.6	–5.9	+1.7	–8.4	+2.2	–6.0	+0.1	–	–
4 m	–4.6	+5.1	–3.8	+3.2	–5.5	+4.1	–4.0	+1.9	–	–
5 m	–3.4	+5.9	–2.3	+4.7	–3.3	+5.7	–2.6	+3.2	–	–
6 m	–2.7	+6.4	–1.2	+5.8	–1.9	+6.4	–1.6	–	–	–

The comparison of HIRHAM5 with a validated SEB model forced by *in situ* observation data (Charalampidis *et al.* 2015) shows good agreement in simulated melt estimates (Fig. 2A). HIRHAM5 slightly underestimates melt in all years (differences less than 31 MJ/m^2) except 2011 (excess of 7 MJ/m^2). The cumulative difference in melt energy between the two models over the course of five melt seasons amounts to 68 MJ/m^2, approximately equal to the total melt in July 2013. This suggests that the positive firn temperature biases are not due to exaggerated melt.

HIRHAM5 substantially underestimates refreezing (Fig. 2B). The differences are less than 15% in all years except 2012, when the difference is 44% and approximately equal to total refreezing in 2013 (380 kg/m^2). With well-simulated melt and underestimated refreezing by HIRHAM5, the firn temperature bias is due to prolonged wintertime refreezing at great depth. As a result of the overestimated latent heat release at depth during every year, HIRHAM5 wintertime low temperature extremes remain at depths no greater than *c.* 3 m (Fig. 1B).

Both HIRHAM5 and Charalampidis *et al.* (2015) overestimate the percolation depth. As analysed by Charalampidis (2016), the SEB model captures the thermal evolution of firn well. The model was initialised on 4 April 2009 based on firn temperature observations, and height-corrected 2012 firn densities, thus calculating realistic cold content (i.e. the required energy to raise firn temperature at 0°C) and heat diffusion estimates throughout the 4.5-year simulation. The SEB model does not calculate liquid water retention, thus all percolating meltwater is refrozen at every time step, which is incorrect close to the surface (2–3 m depth; Fig. 1A). However, no refreezing (i.e. no latent heat release) after the melt season at depth results in more realistic wintertime cooling of deep firn.

HIRHAM5 was initiated more than two decades before 2009. Additionally, the current subsurface scheme of HIRHAM5 cannot reproduce ice layers. This inability results in unrealistic representation of firn stratigraphy, and thus estimation of cold content, which is dependent on firn temperature and density. On 4 April 2009, the thermal state of the subsurface in HIRHAM5 is the integrated result of all previous simulation years, and is already on average 4.6°C too warm in the upper 10 m of firn (Fig. 1C). The associated cold content integrated over the first 10 m is 72 MJ/m^2. By

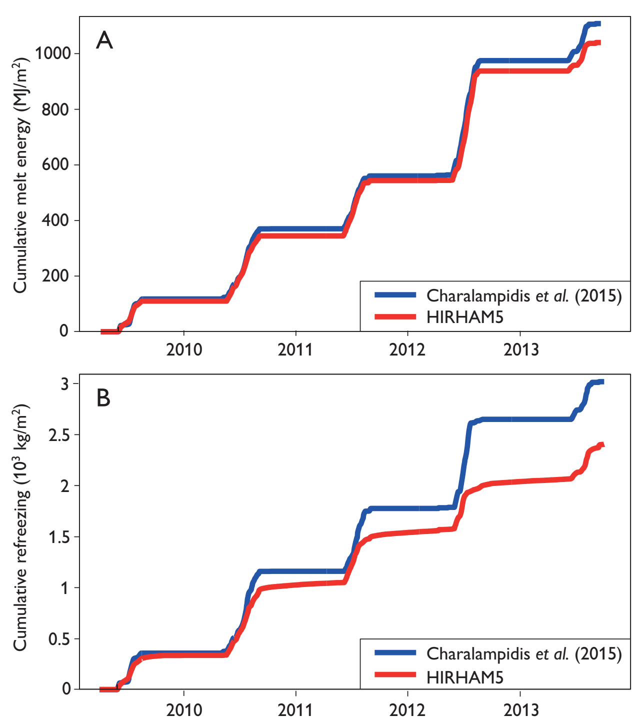

Fig. 2. Cumulative melt energy (**A**) and total refreezing (**B**) at KAN_U by HIRHAM5 and Charalampidis *et al.* (2015).

comparison, the cold content on the same day in Charalampidis *et al.* (2015) is 151 MJ/m^2. One third of the difference in cold content is due to differences in firn density.

Near-complete cold content depletion (i.e. firn temperature at 0°C) of the first 10 m of firn is simulated by HIRHAM5 for 2010. Thereafter, this temperate firn retains liquid water, which refreezes during winter under the influence of subfreezing conditions diffused from the surface. This results in wintertime latent heat release at depth that in 2010 to 2012 is sustained until the beginning of the following melt season (Fig. 2B). Eventually, this premature depletion of cold content leads to overestimation of the percolation depth, liquid water retention and heat in firn.

Concluding remarks

Judging from the simulation of wintertime firn temperatures in the period April 2009 to September 2013, HIRHAM5 is able to realistically reproduce subsurface processes when heat conduction dominates. Yet the comparison of HIRHAM5 with observations and SEB model output reveals an overestimation of the percolation depth, liquid water retention and heat input from refreezing.

For April 2009, HIRHAM5 calculates less than half of the cold content estimate based on observations in the first 10 m of firn. This is the result of the 1989 initialisation of HIRHAM5 and thus the cumulative effect of the imprecise determination of heat diffusion, as HIRHAM5 is unable to adequately represent ice-layer formation in firn. A HIRHAM5 subsurface scheme with improved accounting of shallow firn stratigraphy would greatly improve heat diffusion estimates over long simulation periods, and thus provide more reliable simulations.

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